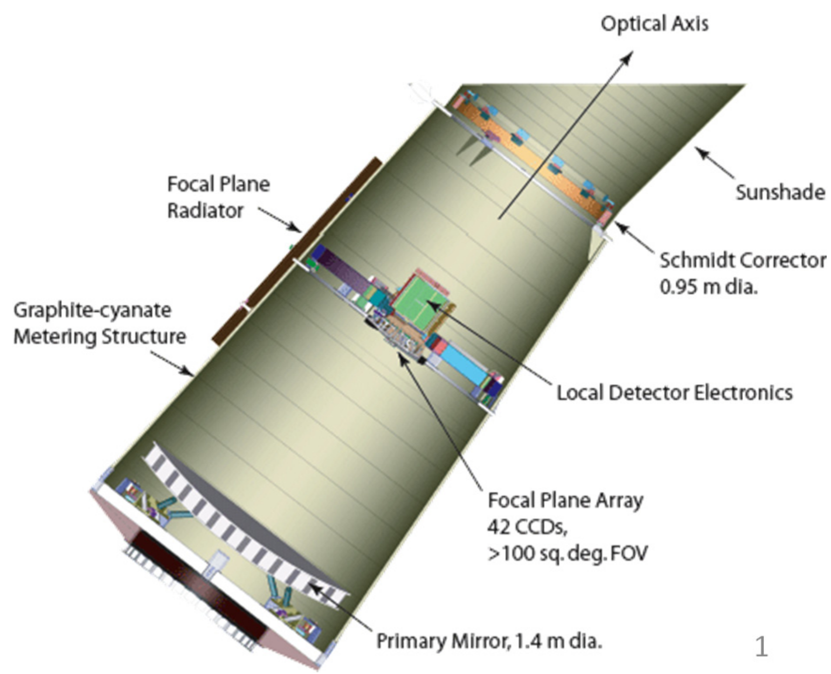
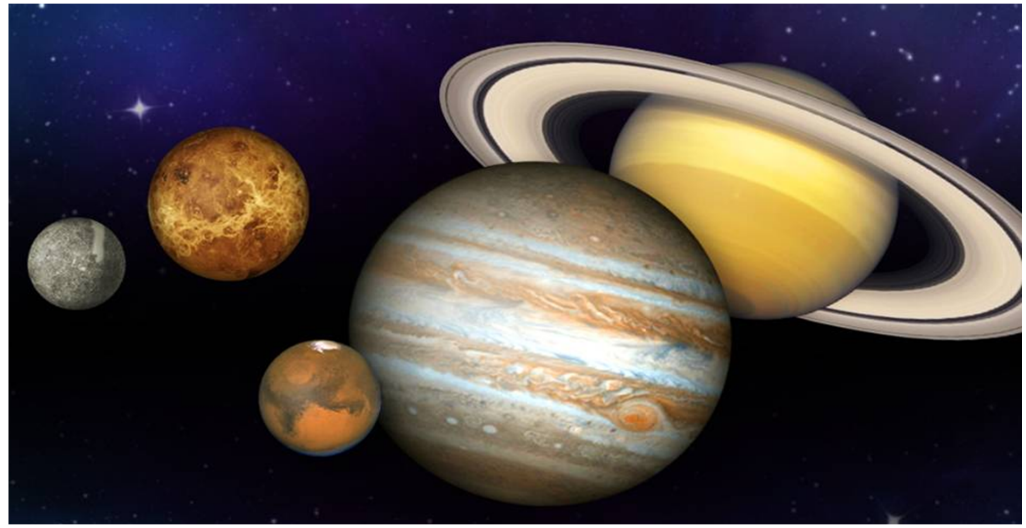
Terrestrial, Habitable-Zone Exoplanet Frequency from Kepler

Wesley A. Traub
Jet Propulsion Laboratory,
California Institute of Technology

Boston University Seminar
13 October 2011



Exoplanets: where & how many?



Outline of talk:

- The Kepler database
- Biases
- The radius distribution
- The period distribution
- Projecting from the sample to the population
- Extrapolating the period distribution
- The Habitable Zone
- Calculating the number of terrestrial, HZ planets
- Conclusions

Exoplanets are a high priority at NASA

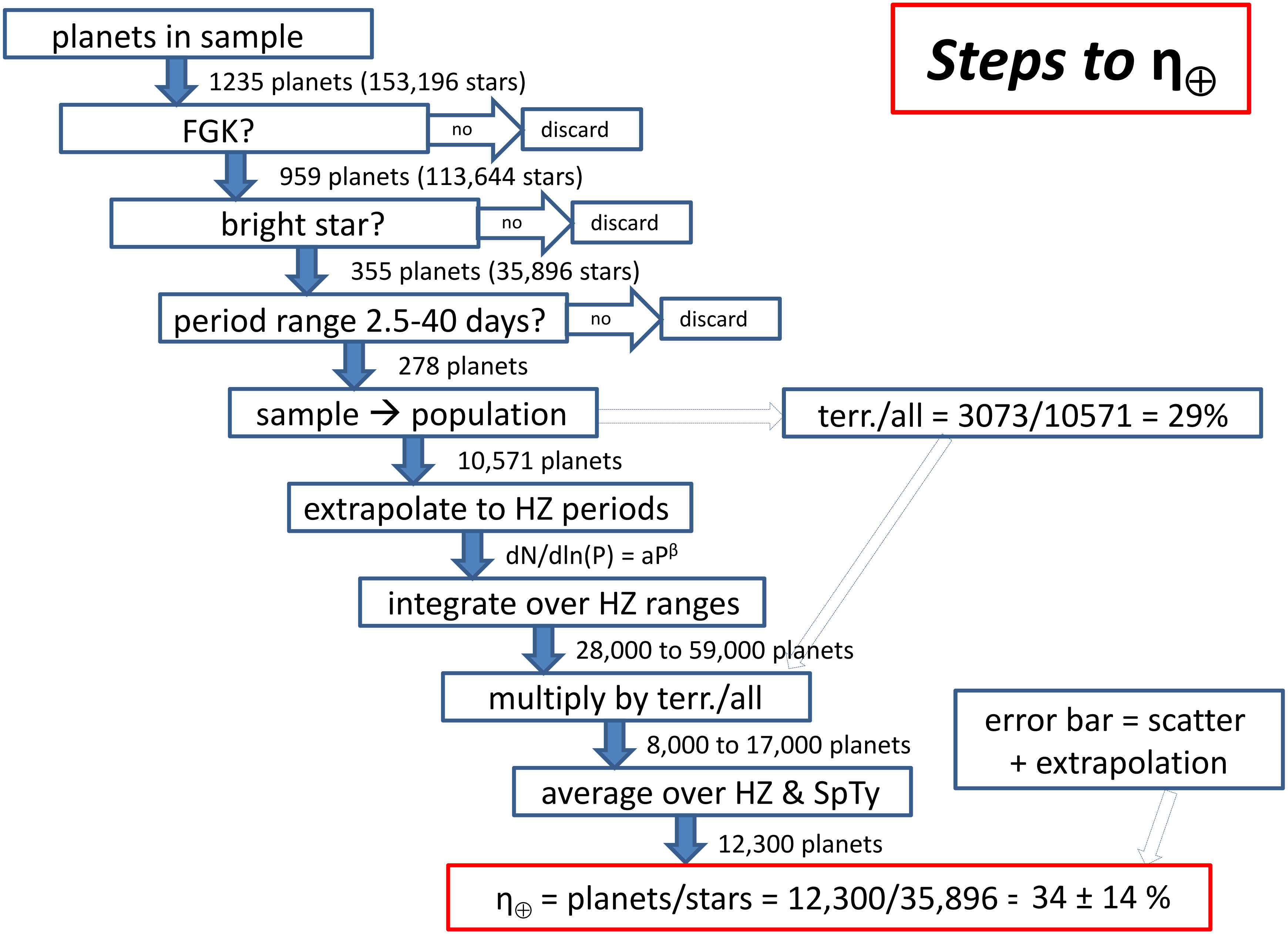
Top priorities for the Astrophysics Division at NASA:

Science Goal:
Discover how the universe works, explore how the universe began and evolved, and search for Earth-like planets.

Science Question (1 of 3):
What are the characteristics of planetary systems orbiting other stars, and do they harbor life?

Science Objective (1 of 3):
Generate a census of extra-solar planets and measure their properties.

The Kepler mission addresses these aspects.



Steps to η⊕
planets in sample
1235 planets (153,196 stars)
FGK?
no
discard
959 planets (113,644 stars)
bright star?
no
discard
355 planets (35,896 stars)
period range 2.5-40 days?
no
discard
278 planets
sample → population
terr./all = 3073/10571 = 29%
10,571 planets
extrapolate to HZ periods
dN/dln(P) = aP^β
integrate over HZ ranges
28,000 to 59,000 planets
multiply by terr./all
8,000 to 17,000 planets
error bar = scatter + extrapolation
average over HZ & SpTy
12,300 planets
η⊕ = planets/stars = 12,300/35,896 = 34 ± 14 %

Temperature condition

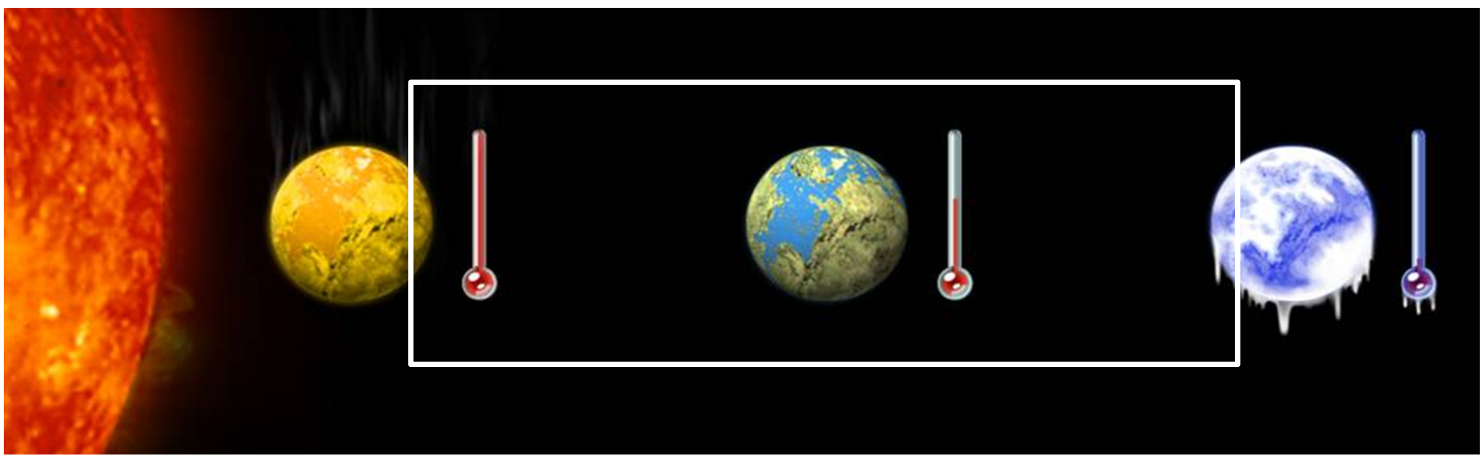
Liquid water is necessary for life (an assumption).

A habitable planet must have liquid water on its surface.

The surface temperature must allow liquid water.

T(surface) = T(equilibrium) + T(internal) + T(greenhouse)

So the HZ is the range of distances from a star
that allows liquid water on the surface.



Radius condition

A terrestrial planet has a rocky core and a comparatively negligible atmosphere.

So the surface is solid or liquid.

Planet formation models show that cores larger than about 10 Earth masses will likely accumulate a very large atmosphere, very quickly, and become a Jupiter, Saturn, Uranus, or Neptune.

But 10 Earth masses implies about 2 Earth radii.

Mars can barely hold on to its atmosphere, at 0.1 Earth mass and 0.5 Earth radius.

So a terrestrial planet is taken to have a radius of 0.5 to 2.0 Earths.

What on Earth is $\eta_\oplus$ (eta-sub-Earth)?

A habitable planet is a terrestrial body in the HZ of its star.

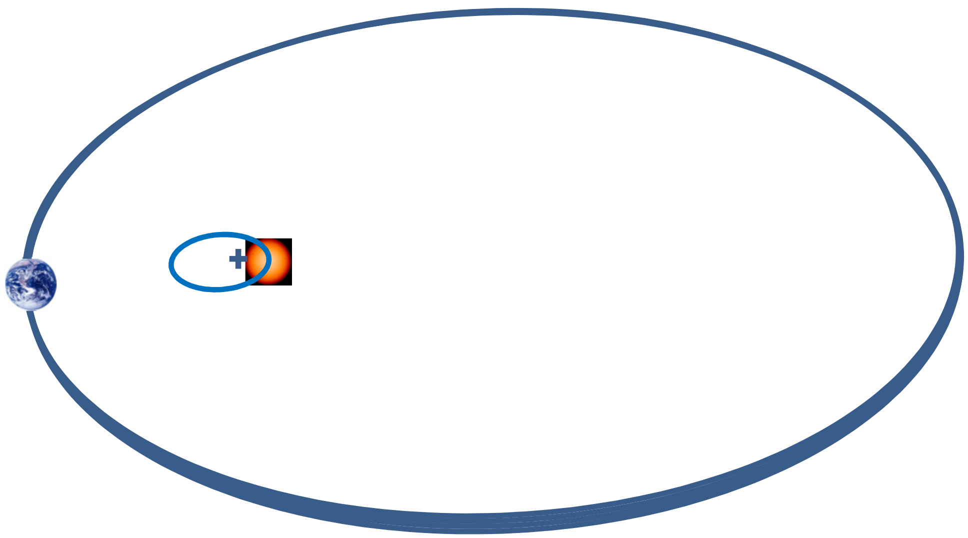
$\eta_\oplus$ is the average number of habitable planets per star.

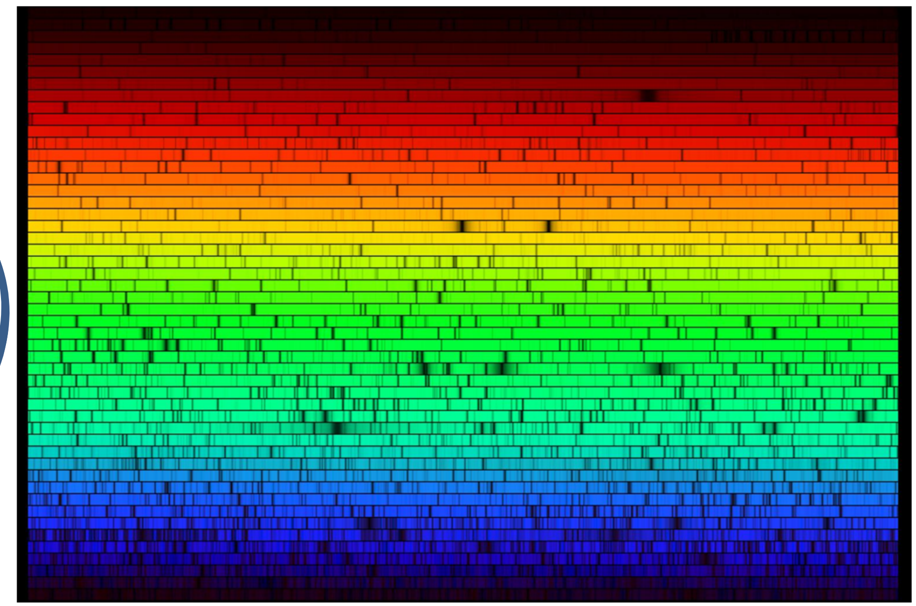
If we include potentially habitable planets,
then $\eta_\oplus \cong 3$ in the Solar System.

The Kepler data tell us the semi-major axis and star luminosity,
therefore giving an estimate of the surface temperature.

The Kepler data tell us the radius of a planet,
therefore if it is in the terrestrial-size range.

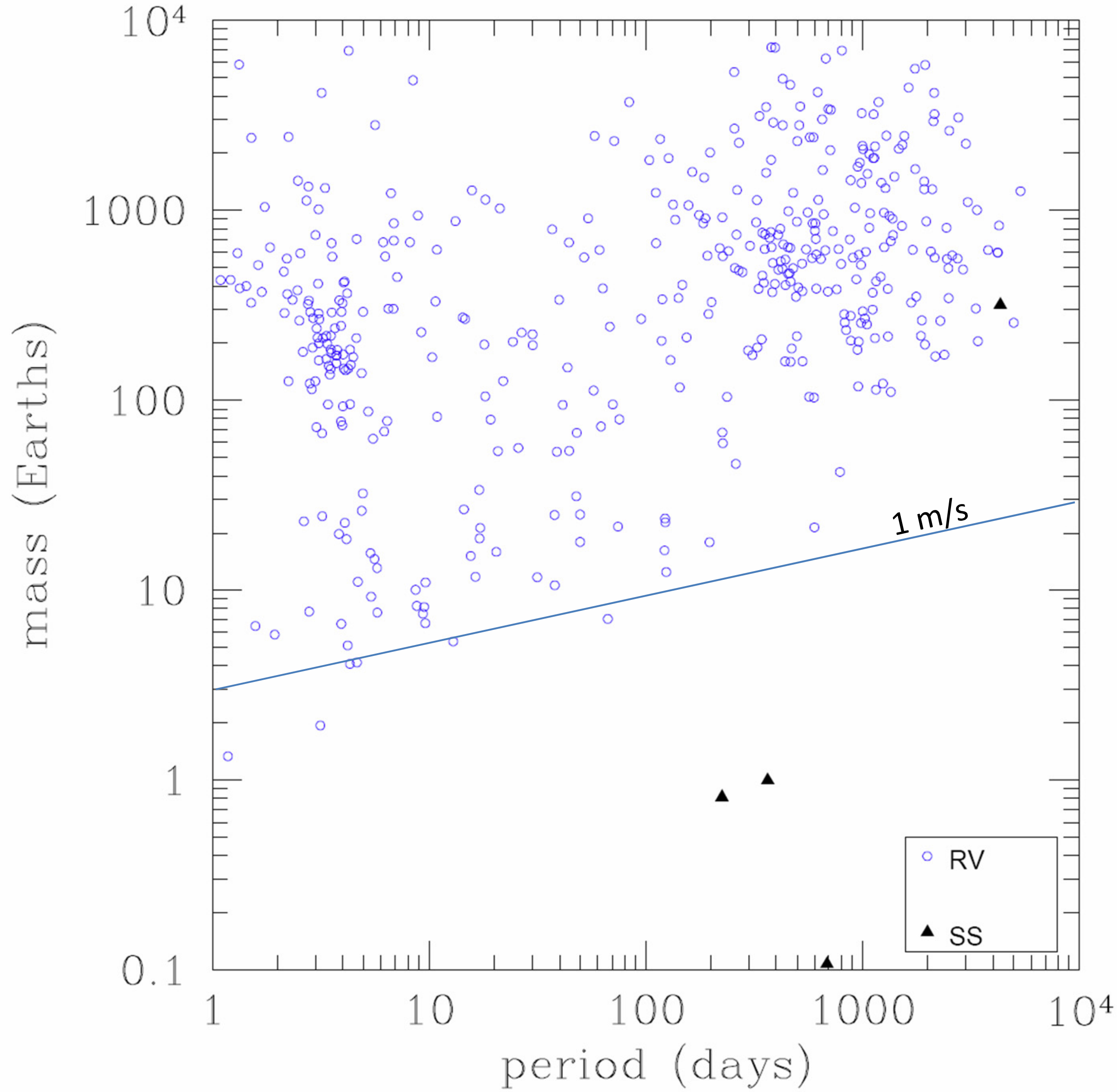
Radial Velocity



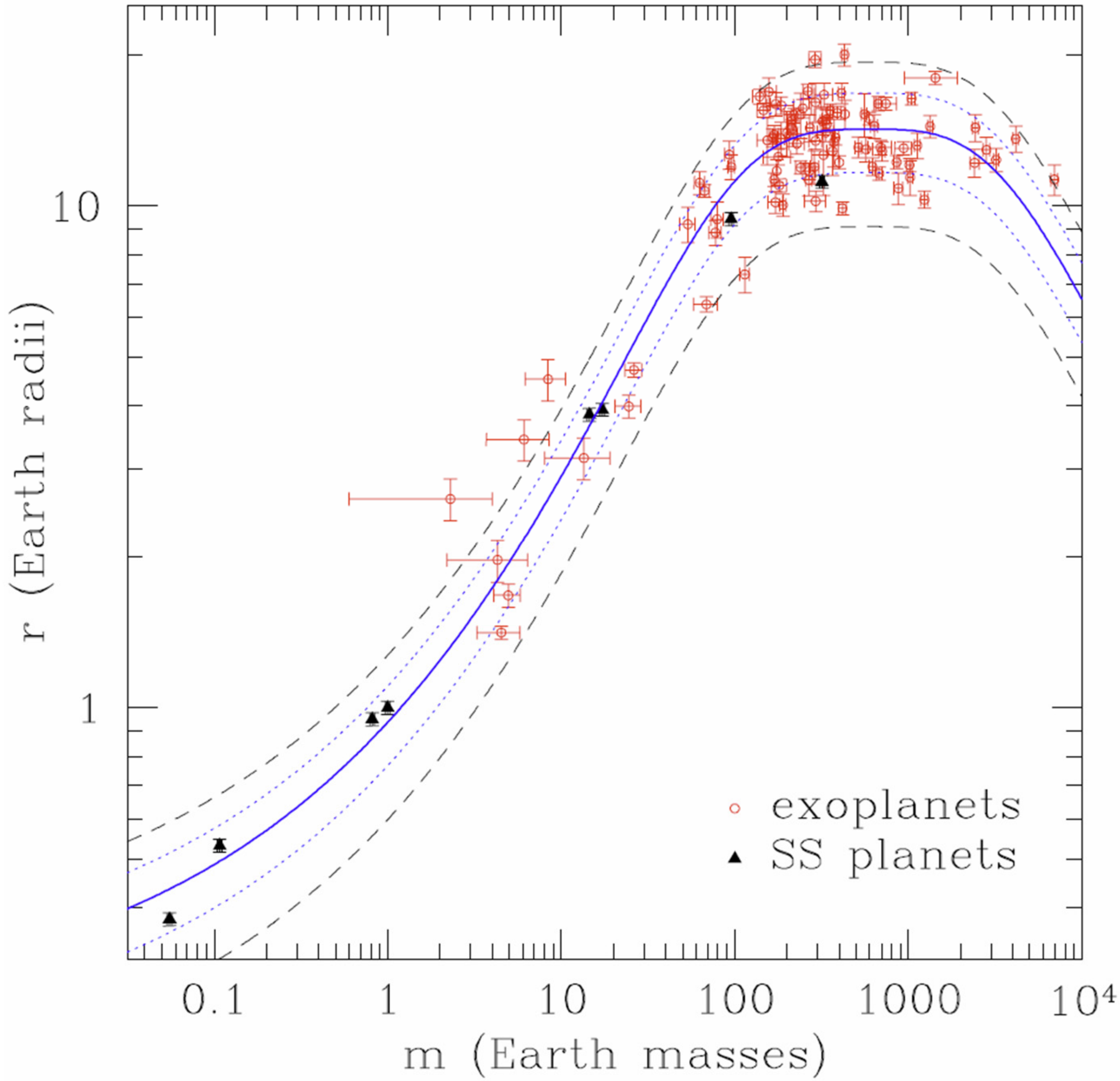


$$m_{Earth} \cdot \sin(i) \approx \frac{(v_{\max} - v_{\min})/2}{0.1m/s} \cdot M_{sun}^{2/3} \cdot P_{yr}^{1/3} \cdot \sqrt{1-e^2}$$

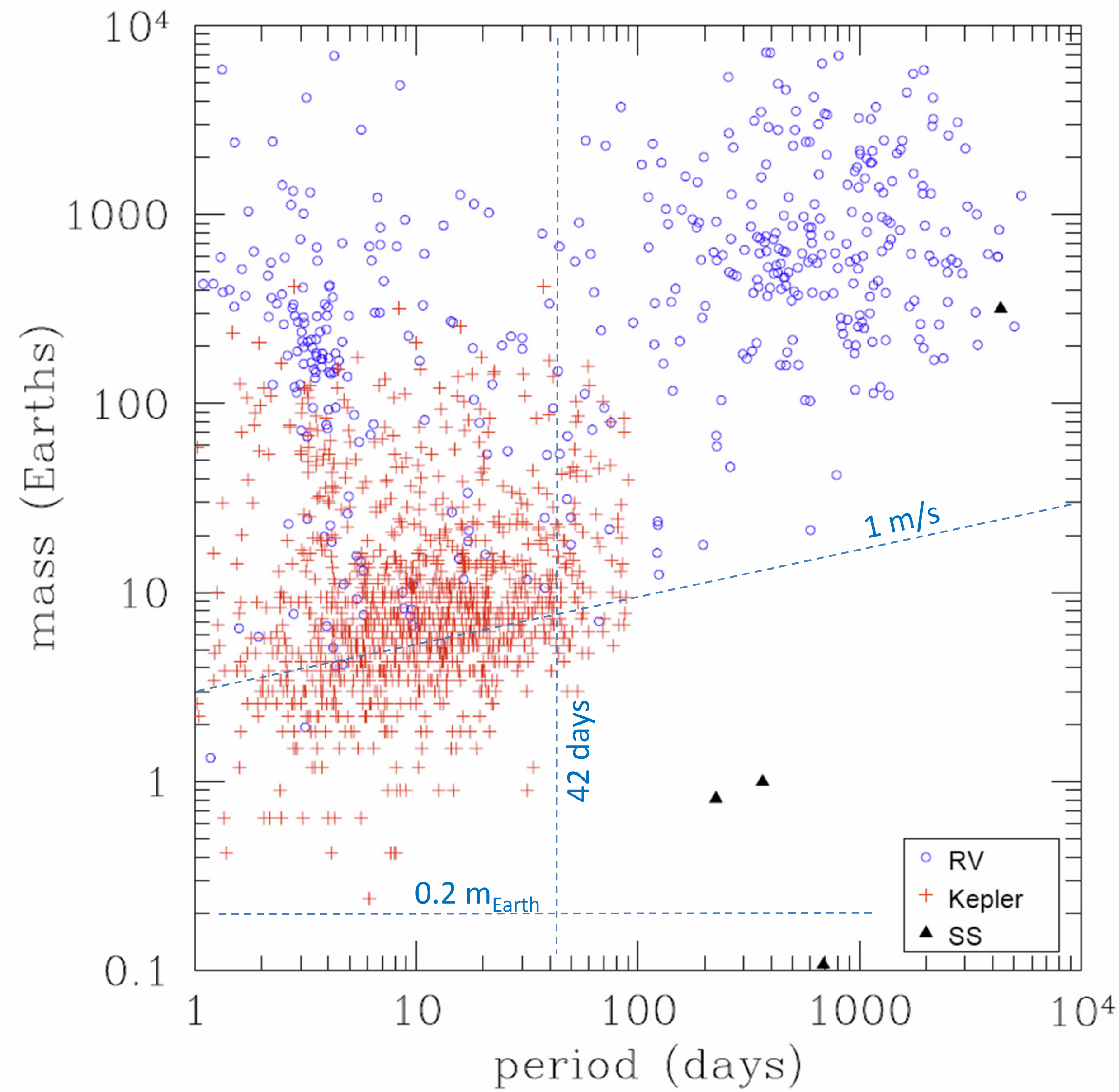
Mass *vs* period from RV



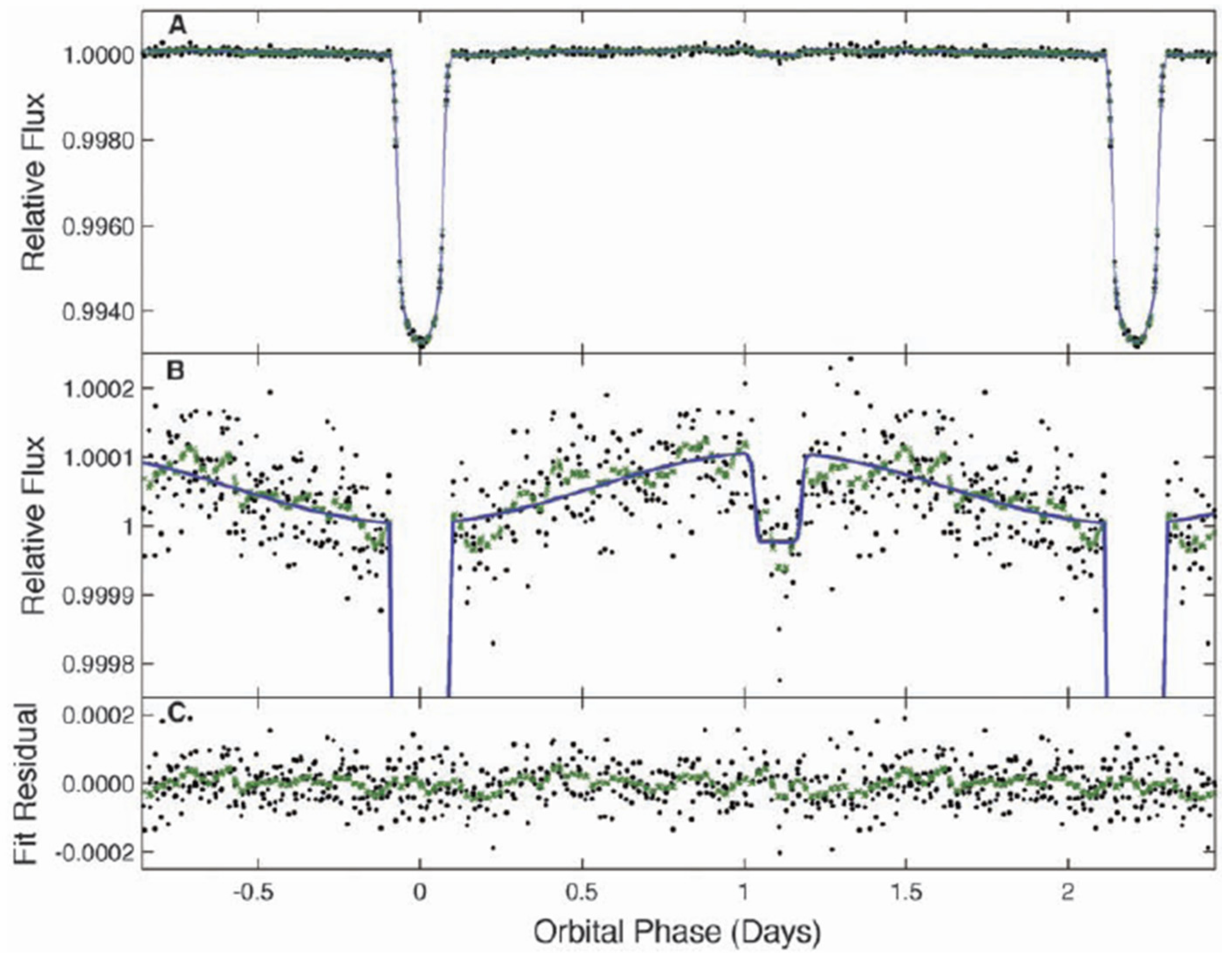
Radius vs mass from transits+RV

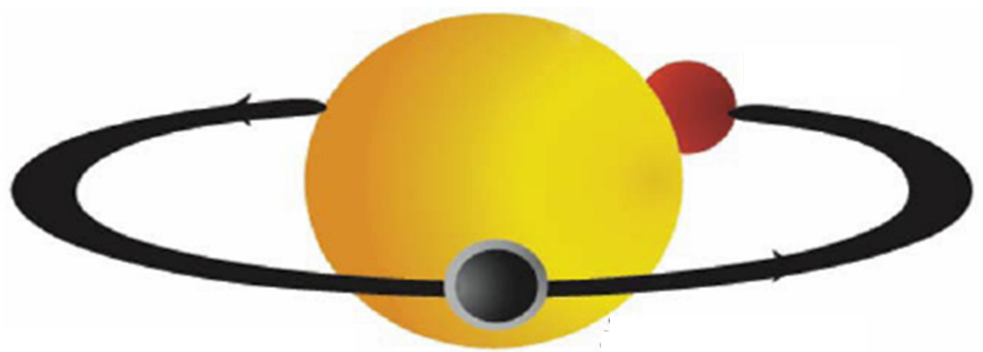


Mass *vs* period from RV & Kepler



Transits


A
B
C.
Relative Flux
Relative Flux
Fit Residual
1.0000
0.9980
0.9960
0.9940
1.0002
1.0001
1
0.9999
0.9998
0.0002
0.0000
-0.0002
-0.5
0
0.5
1
1.5
2
Orbital Phase (Days)



The Kepler database (the “sample”)

11 Feb. 2011 database covers mission quarters Q1,2,3 = 136 days

153,196 target stars

- 20,406 F stars (T_s = 6000-6500 K)
- 55,595 G stars (T_s = 5500-6000 K)
- 37,643 K stars (T_s = 5000-5500 K)
- 113,644 total

1235 planets (“planetary candidates”)

- 159 F-star planets
- 475 G-star planets
- 325 K-star planets
- 959 total

Period sampling is complete up to 136/3 ~ 42 day periods.

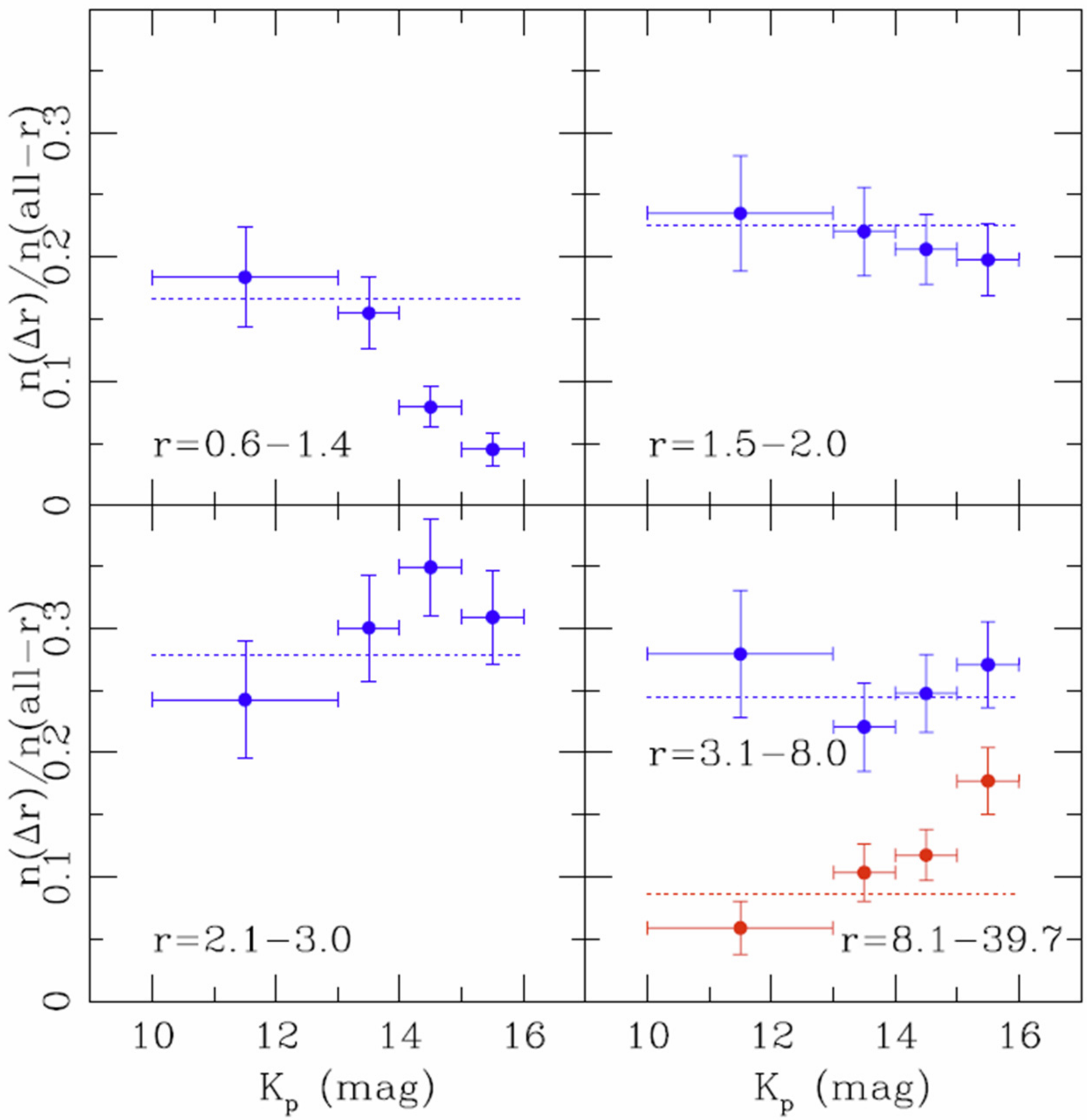
Bias estimation

- Field-of-view bias
- Magnitude-limit bias
- Active-star bias
- Star-spot bias
- Stellar-parameter bias
- Spectral-class bias
- Impact-parameter bias
- False-positive bias
- Planet-radius bias
- Period-completeness bias
- Distribution-function bias
- Mission-length bias

Radius bias, magnitude dependence

Faint star & small planet → weak signal → noise could mask the signal

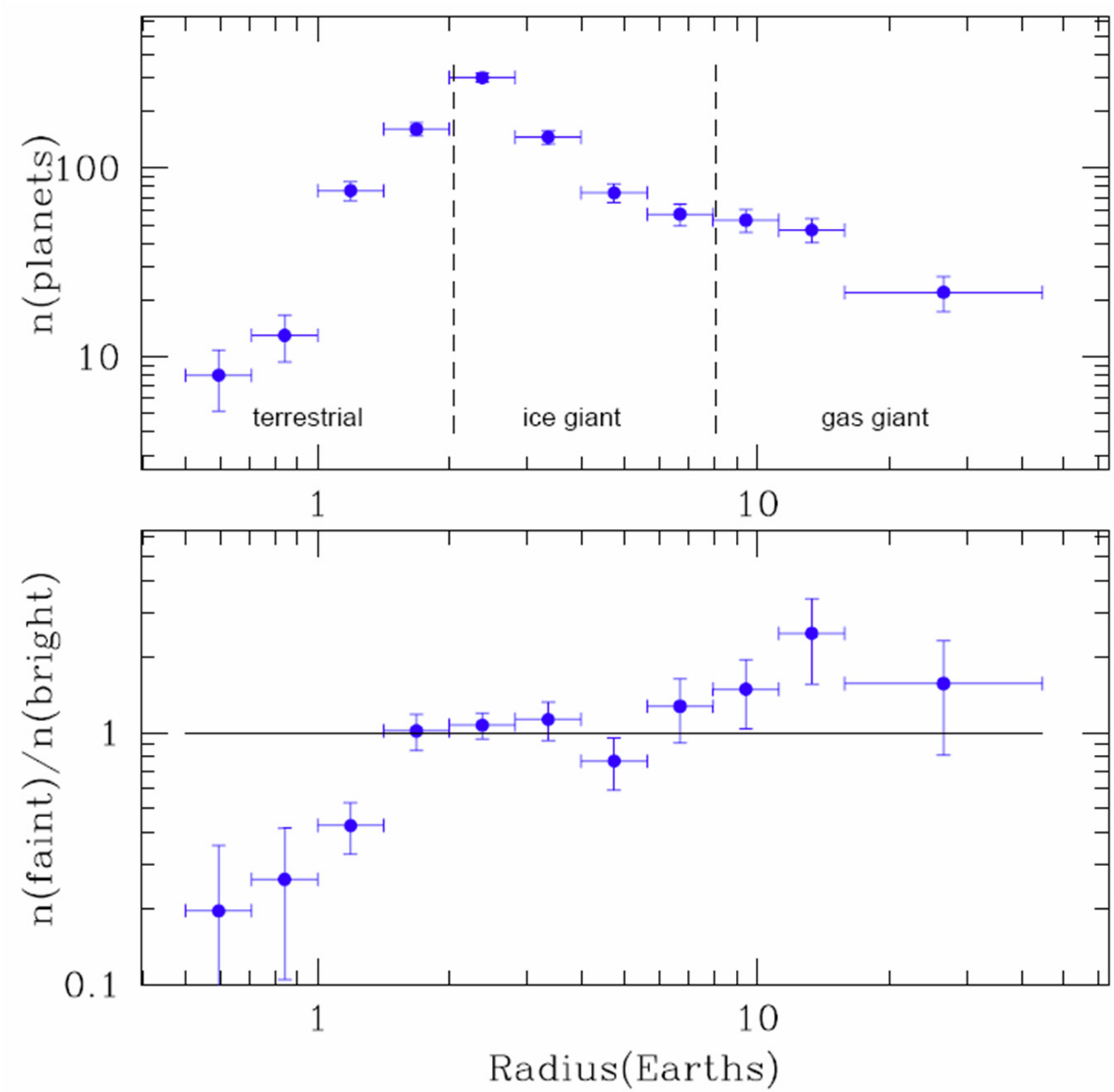
Planets *vs* star magnitude, in sample



Radius bias: mid-size planets

It would be a good sign if mid-size planets
(not too small, not too large)
were equally detected around bright & faint stars.

No. of planets *vs* radius, in sample



Radius bias: bright vs faint stars

Because database is biased against small planets ($r<1.4$),
around faint stars ($K_p>14$),
we next focus on the bright stars only.

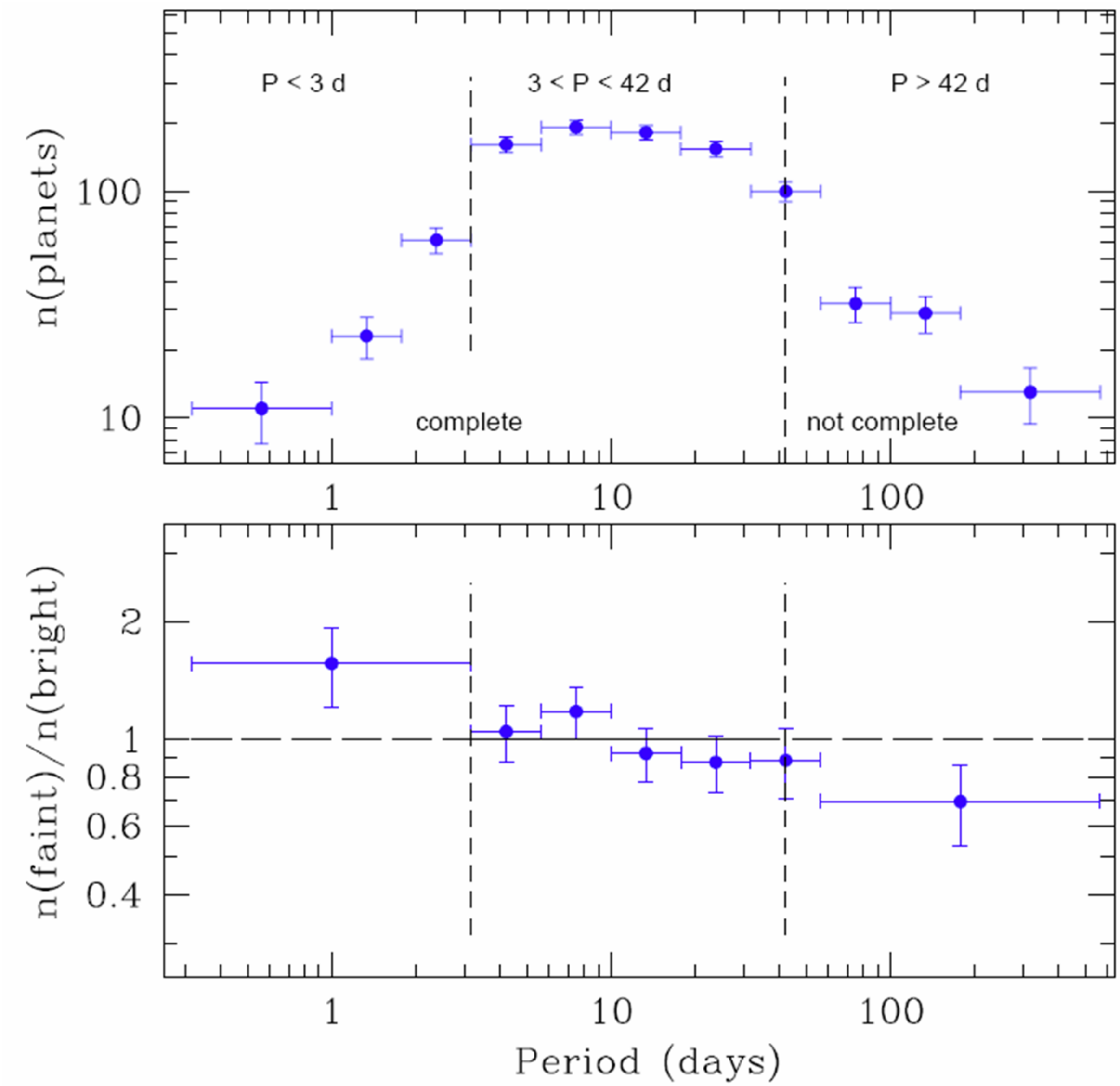
So FGK targets go from 113,644 → 35,896 stars,
and 959 → 355 planets.

Period distribution in the sample

Here too, look to see if the number of planets in each period bin is the same (or not) for bright vs faint target stars.

We do find a slight trend, but believe that this is a SNR effect.

No. of planets *vs* period, in sample



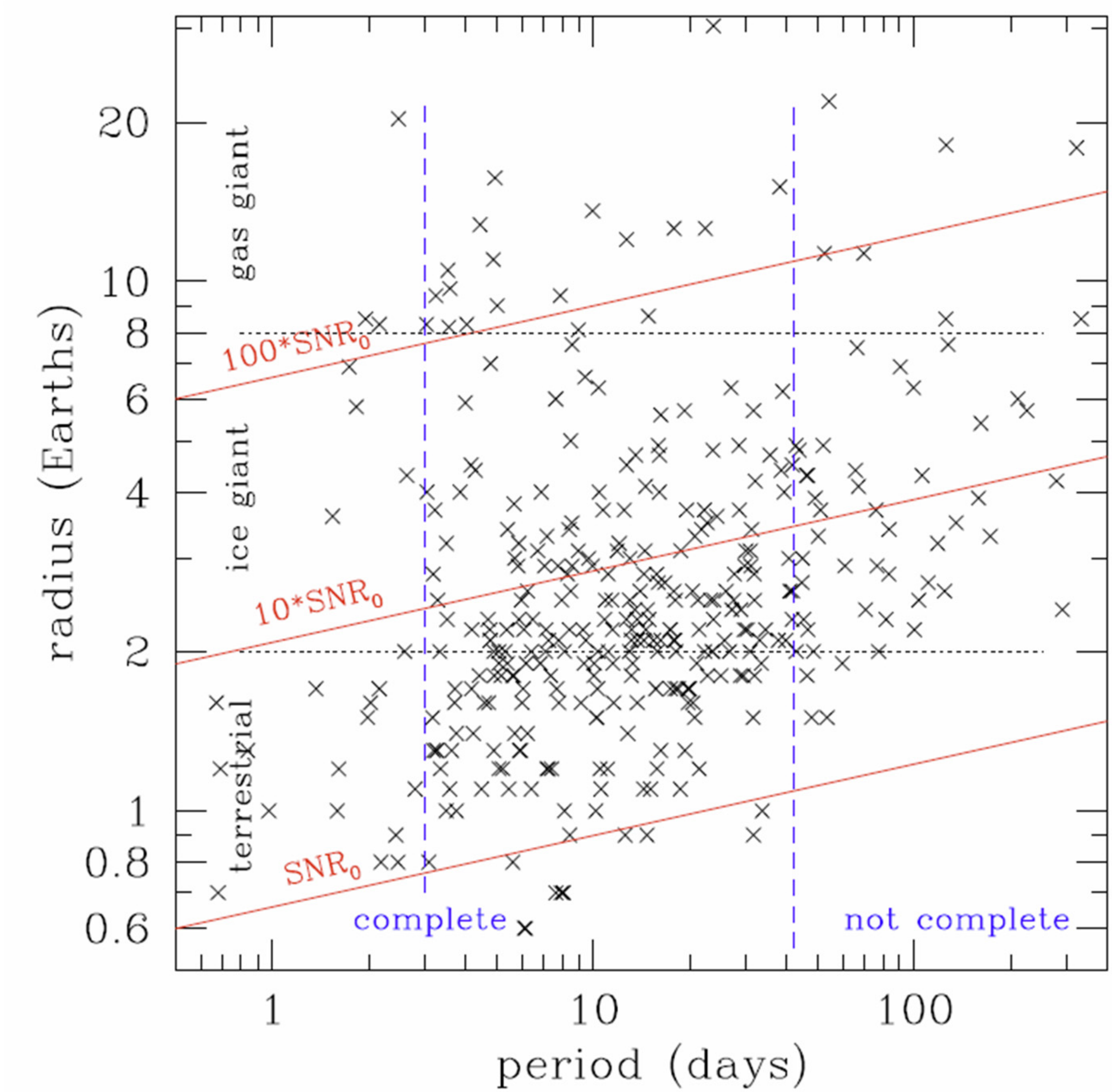
Period-radius scatter diagram

A scatter diagram gives an overall look at the bright-star planets, as a function of period and radius.

We look for groups of data, and trends, and try to understand both.

Note that the detection threshhold is SNR > 7 per transit,
and SNR ~ signal/noise,
and signal ~ transit time * (planet/star) area ~ $P^{1/3}r^2$
but noise ~ (transit time)$^{1/2}$
and multiple transit factor ~ (number of transits)$^{1/2}$
so net SNR ~ $P^{-1/3}r^2$
so line of constant SNR is given by $\mathbf{r = (SNR/SNR_0)^{1/2}P^{1/6}}$

No. of planets *vs* radius & period, in sample



Transit probability

Probability of transit is p_t = R(star)/a(orbit)

So for each detected transit in the **sample**,
there are a total of 1/pt planets in the **population**.

Thus $N_p = 1/p_t(1) + \ldots + 1/p_t(n_{obs})$.

Period distribution in the population

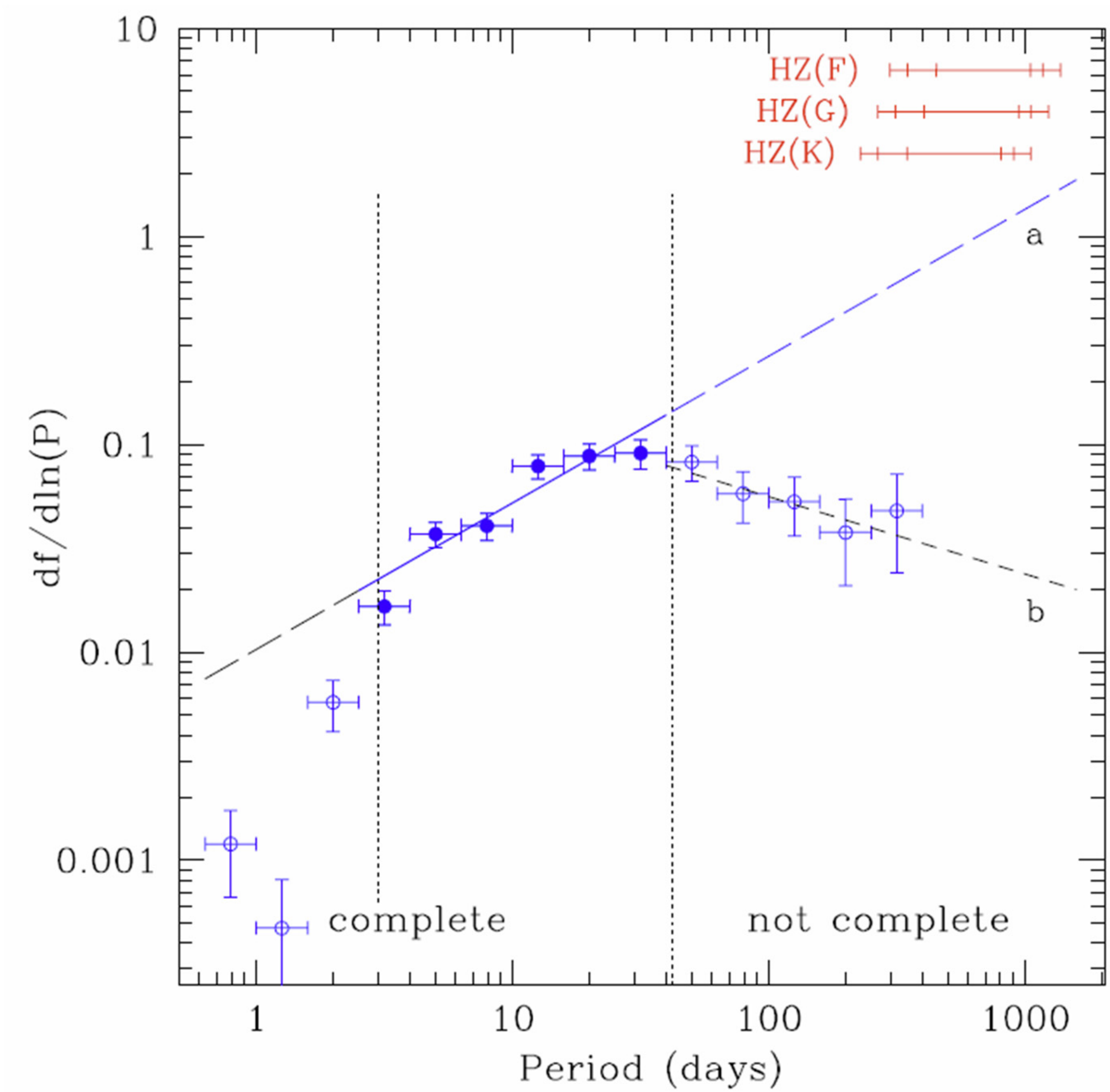
Let $f(P)$ = no. of planets / no. of stars.

The plot of binned $f(P)$ vs P → power law relation

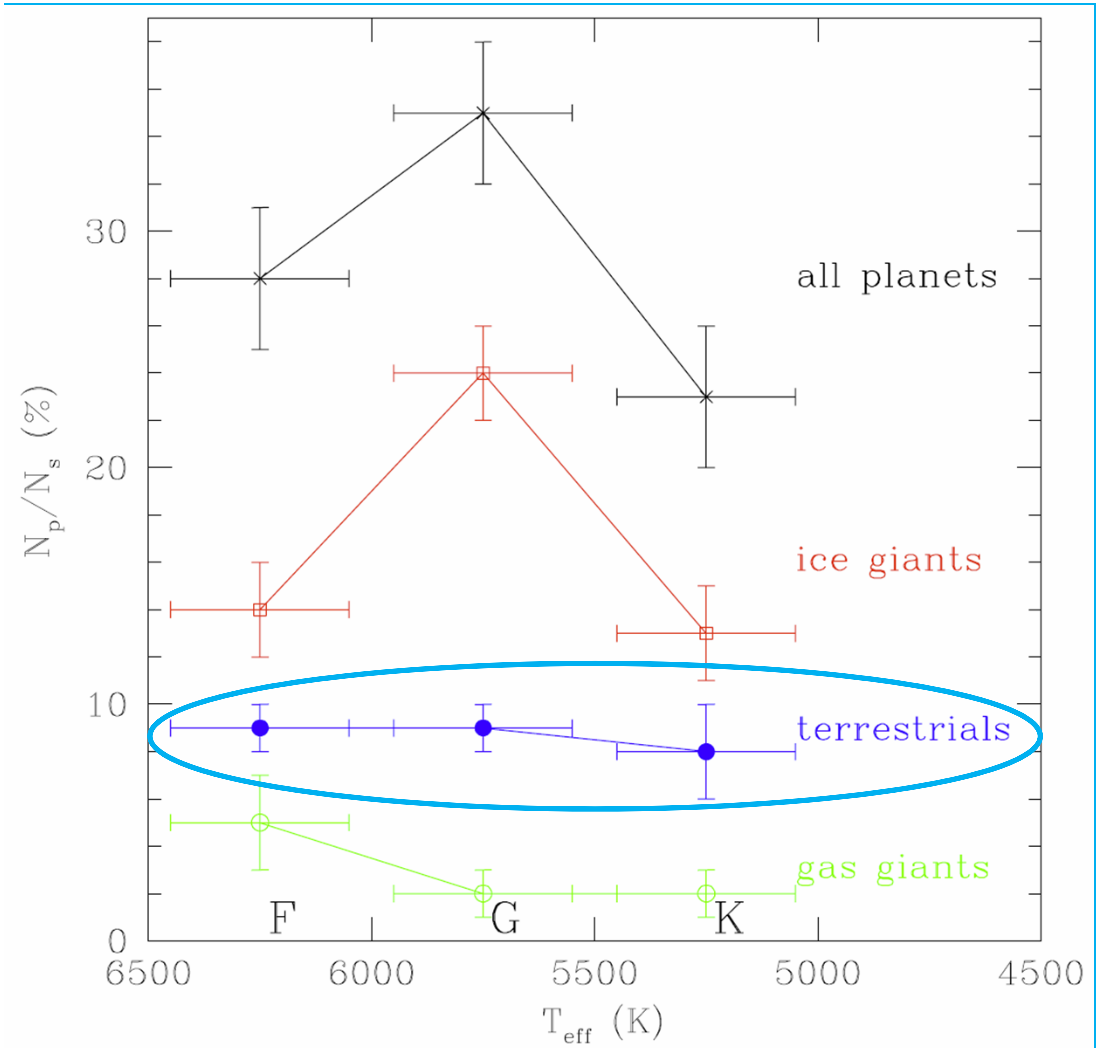
or $df/d\ln(P) = A \cdot P^{\beta}$

or $df/dP = A \cdot P^{\beta-1}$

No. of planets *vs* period, in population



Planet types *vs* star **spectral types** in population



SpTy	$\frac{N_p(terr)}{N_s}$ (%)	$\frac{N_p(ice)}{N_s}$ (%)	$\frac{N_p(gas)}{N_s}$ (%)	$\frac{N_p(all)}{N_s}$ (%)
F	9 ± 1	14 ± 2	5 ± 2	28 ± 3
G	9 ± 1	24 ± 2	2 ± 1	35 ± 3
K	8 ± 2	13 ± 2	2 ± 1	23 ± 3
FGK	9 ± 1	18 ± 1	3 ± 1	29 ± 2

Close-in (P < 42 days), terrestrial-size planets are found around about 9% of each of F, G, K stars.

Habitable zone

Wide HZ: 0.72 AU (Venus) to 2.00 AU (Mars 1.52 +)
ensures including all conceivable planets that could be habitable

Nominal HZ: 0.80 AU to 1.80 AU
recommended by TPF-C project in 2006, a "best bet"

Narrow HZ: 0.95 AU to 1.67 AU
gives a lower limit on $\eta_{\oplus}$, to make sure we build TPF large enough.

Convert from Sun to other star period using

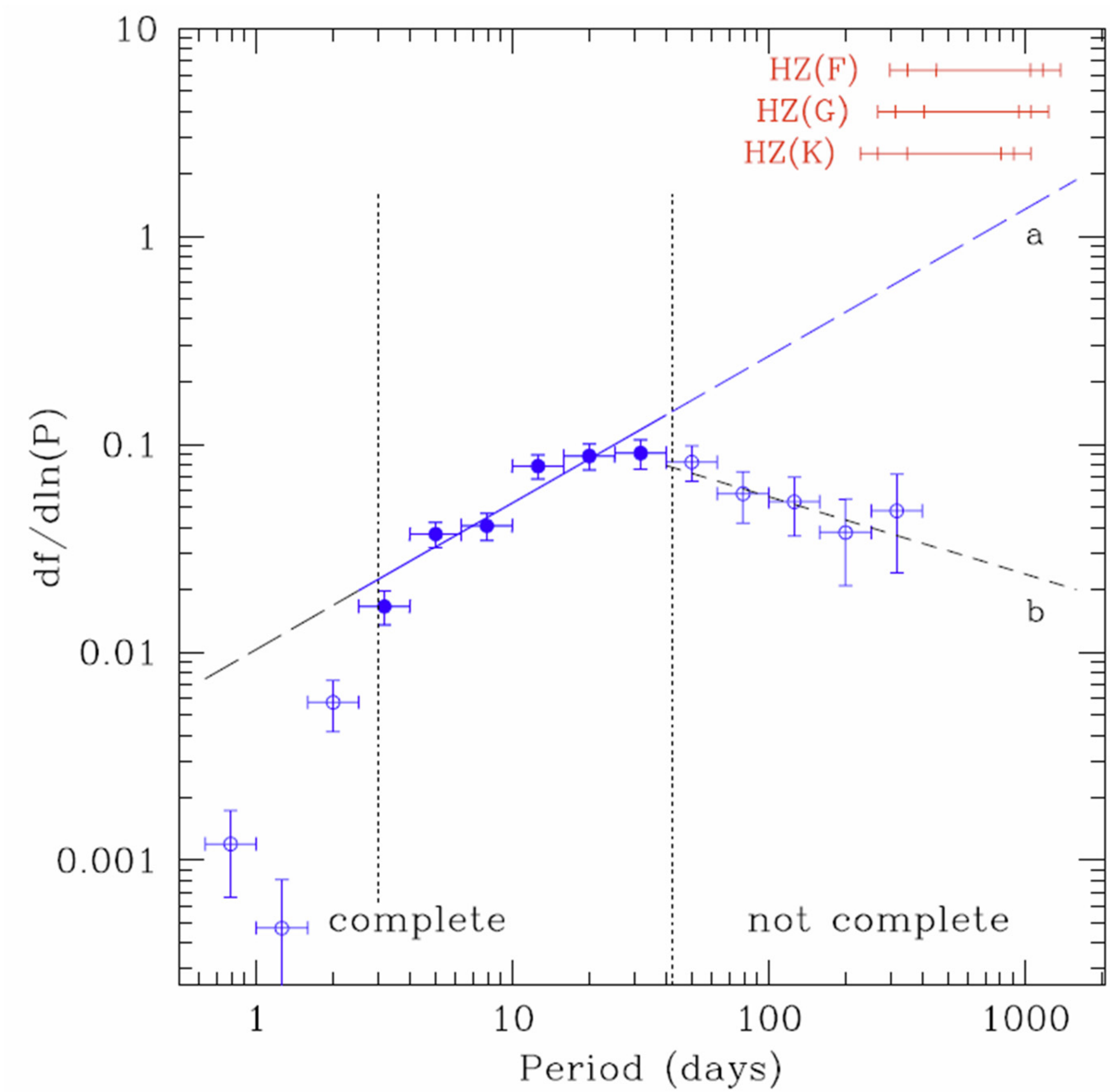
$a \sim L^{0.5}$

and $L \sim M^{3.8}$

and $P^2 \sim a^3/M$

so $P(\text{days}) = 365 \cdot M^{2.35} \cdot a_{sun}^{1.5}$

No. of planets *vs* period, in population



$\eta_\oplus$ calculation

Integrating all planets under the extrapolated curve gives

$$f2 - f1 = A(P_2^\beta - P_1^\beta) / \beta$$

Specialize to terrestrial fraction:

$$\rho_\oplus = N_p(\text{terr}) / N_p \cong 0.29$$

so net result is

$$\eta_\oplus = \rho_\oplus \cdot A \cdot (P_2^\beta - P_1^\beta) / \beta$$

Averaging over the HZs and spectral classes gives

$$\eta_\oplus = 34 \pm 14\ \%$$

HZ type	$\eta_\oplus(F)$	$\eta_\oplus(G)$	$\eta_\oplus(K)$
Case 1	0.47	0.44	0.39
Case 2	0.37	0.34	0.31
Case 3	0.27	0.25	0.22

Steps to $\eta_\oplus$

planets in sample

1235 planets (153,196 stars)

FGK? — no → discard

959 planets (113,644 stars)

bright star? — no → discard

355 planets (35,896 stars)

period range 2.5-40 days? — no → discard

278 planets

sample → population → terr./all = 3073/10571 = 29%

10,571 planets

extrapolate to HZ periods

$dN/d\ln(P) = aP^{\beta}$

integrate over HZ ranges

28,000 to 59,000 planets

multiply by terr./all

8,000 to 17,000 planets

average over HZ & SpTy

12,300 planets

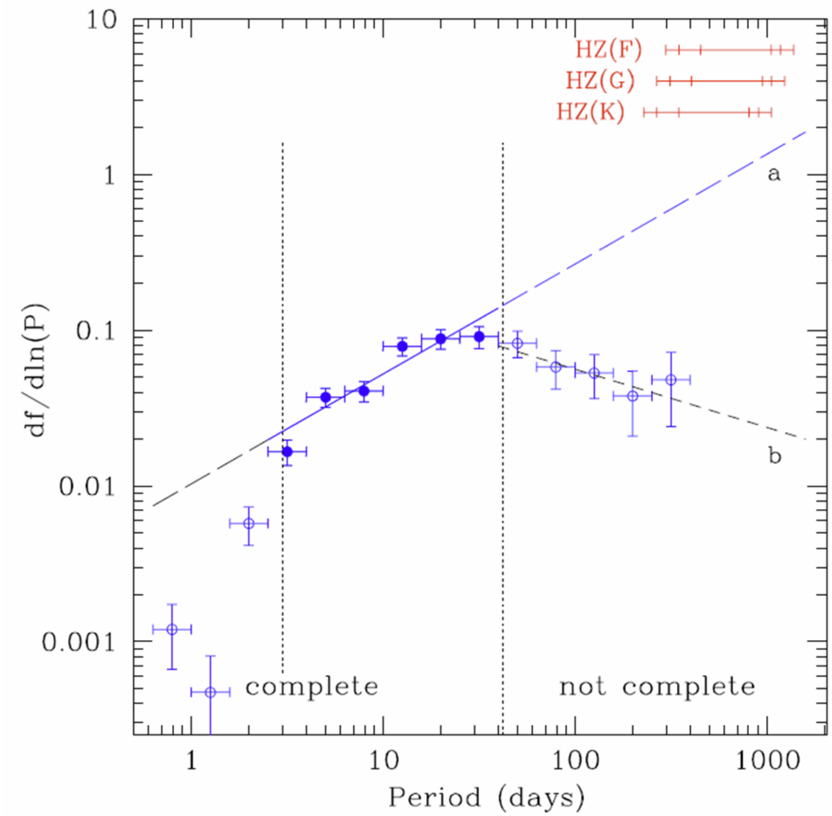
error bar = scatter + extrapolation

$\eta_\oplus$ = planets/stars = 12,300/35,896 = 34 ± 14 %

Comparison to Catanzarite & Shao 2011

If we think that the "not complete" numbers
are in fact "complete",
then curve b is the extrapolation,
and the area under the curve will be ~ 30 times less.

This is the result given by C&S 2011, i.e., 1-3 %.



Comparison to Solar System

In the Solar System, using P_1 = P(Venus) and P_2 = P(Mars), we find

$$\eta_{\oplus}(SS) \cong df/d\,ln(P) \;\cong\; (3\text{-}1)/ln(686/224) \;\cong\; 1.8$$

which is ~5 times larger than 0.34, however Kepler has not yet sampled beyond the orbit of Mercury, so there is still room for more planets to be discovered.

Note that this also says that the target planet systems are less “filled” than the Solar System, but since the SS is dynamically stable, then certainly these other systems are stable too.

Future prospects

The Kepler data are still rolling in.

Q4 will be released soon.

Q5,6,7 will be released in January 2012,
and Q8,9,10 several months later.

A decision on extending the mission beyond 3.5 years
will be made by a Senior Review committee in February 2012.

This could allow the full HZ to be observed.